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WORKING TITLE: Broadening Student Consideration of Sustainability Factors in Engineering Design Decisions: Evidence from a Course-Based Intervention (Work-In-Progress)

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Broadening Student Consideration of Sustainability Factors in Engineering Design Decisions: Evidence from a Course-Based Intervention (Work-In-Progress)

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1. Introduction

Engineering design is fundamentally characterized by ill-structured problems that lack a singular "correct" solution and require students to navigate high levels of ambiguity, complex trade-offs, and incomplete information (Dringenberg et al., 2018; Francis et al., 2022). In the context of sustainability, this complexity is magnified as engineers must evaluate competing objectives across global, cultural, environmental, and economic domains (Zorn & Malz, 2023). Despite the critical nature of these decisions, engineering education often reinforces a "techno-economic" bias, where students prioritize quantifiable metrics like cost and performance while sidelining broader sustainability considerations such as chemical persistence or life cycle impacts (Francis et al., 2022; Mesa et al., 2021).

This narrow focus is often a result of bounded rationality and the cognitive strategy of "satisficing" where individuals, limited by cognitive load and time, seek the first solution that is "good enough" based on a familiar, restricted set of criteria (Simon, 1957, 1990). While traditional curricula emphasize formal, mathematical reasoning that converges on single answers, real-world sustainable design demands "informal reasoning," which includes the ability to integrate diverse perspectives, manage uncertainty, and negotiate ethical complexities (Dringenberg et al., 2018; Mares-Nasarre et al., 2023).

Transitioning students from narrow satisficing toward holistic Engineering Judgment is a recognized imperative, as evidenced by ABET's inclusion of the ability to "use engineering judgment to draw conclusions" as a key student outcome (ABET, 2025). However, educators still lack actionable frameworks to intentionally develop and assess this capacity in students (Francis et al., 2022). Furthermore, while there is growing agreement on the key sustainability competencies professionals should possess, most notably systems-thinking, strategic-thinking, and values-thinking (Wiek et al., 2011), the practice of assessing these competencies within the engineering classroom remains in its infancy (Redman et al., 2021).

This study addresses these gaps by examining a course-based intervention designed to broaden student evaluative frameworks through Multi-Criteria Decision-Making (MCDM). In professional practice, MCDM methods serve as robust decision-support systems that convert subjective judgment into rational, transparent procedures (Zavadskas et al., 2020). By using MCDM as a pedagogical scaffold, this intervention aims to make "invisible" trade-offs visible and explicitly manageable for students. Through structured case studies and project-based assignments, this work explores whether explicit practice with MCDM can help students cross a cognitive threshold, moving from simple techno-economic optimization toward the multidimensional judgment required for socially responsible and sustainable engineering (Francis et al., 2022; Zorn & Malz, 2023).

2. Methods

2.1 Course and Participants

The course intervention, titled Green Engineering, is a 10-week quarter long course offered for senior undergraduate chemical and environmental engineering students (N= 41) to take as an optional technical elective. In the course, students are introduced to the concept of sustainability, lifecycle assessment, green engineering principles and green chemistry. They learn various metrics used to assess sustainability and environmental impact, conduct their own lifecycle analysis, and practice multi-criteria decision making using a weighted sum model to select preferred chemicals or design choices via brief case study homework problems, a comparative lifecycle assessment project, and in-class discussions.

2.2. Instructional Intervention: Mapping Activities to Competencies

The course intervention was grounded in the Key Competencies in Sustainability (KCS) framework (Wiek et al., 2011), specifically targeting systems-thinking, anticipatory, and normative competencies. The curriculum was scaffolded to move students from understanding individual metrics to managing complex trade-offs. Specific course activities were mapped to target competencies as follows:

- Defining 'sustainability' and current environmental challenges (weeks 1-2)
- Lifecycle Assessment (LCA) (Weeks 3-5):
    - *Activity:* Lectures, practice problems, in-class discussions, and a quarter-long project where students quantified the cradle-to-grave impacts of two competing products (e.g., paper vs. plastic bags).
    - *Target Competency:* Anticipatory & Systems Competence. This required students to map complex supply chains, analyze impacts across temporal and spatial scales, and anticipate unintended consequences of design choices (Redman et al., 2021).
- Green Chemistry & Engineering Principles (weeks 5-9):
    - *Activities:* Lectures, problem sets, in-class discussions, and comparative case studies engaging with the 12 Principles of Green Chemistry.
    - *Target Competency:* Systems-Thinking. Students learned to analyze how molecular-level design decisions propagate to create system-level environmental hazards (persistence, toxicity, resource depletion, etc.), establishing the technical basis for sustainability.
- Multi-Criteria Decision-Making (MCDM) (Throughout weeks 4-9):
    - *Activity:* Explicit instruction on weighted sum decision making and tradeoffs. Students applied these tools to "messy" case studies where cost conflicted with safety or environmental metrics.
    - *Target Competency:* Normative Competence. By forcing students to assign numerical "weights" to qualitative factors (e.g., "How much do we value toxicity reduction vs. cost savings?"), the MCDM exercises scaffolded the development of values-based reasoning, making invisible ethical trade-offs explicit and calculable (Zavadskas et al., 2020).

2.3. Data Collection and Analysis

To assess changes in students' evaluative frameworks, a pre- and post-course survey was administered. Students were presented with a design scenario and asked to select the factors they would consider when comparing two processes or products from a list of 12 predefined sustainability attributes (e.g., cost, performance, risk, emissions, toxicity, life cycle impacts, bioaccumulation). While many sustainability assessments rely on self-perceived confidence (Redman et al., 2021), this study utilized a cognitive mapping approach to measure the actual breadth of the students' mental models.

Pre/post responses were converted into binary vectors representing the presence (1) or absence (0) of each factor in the student's decision framework. Differences in factor selection frequencies were analyzed using McNemar's test, with *p*-values adjusted for multiple comparisons using the False Discovery Rate (FDR). Changes in the overall 'breadth of thinking (total number of factors selected) were evaluated using paired t-tests and Cohen's *d* effect size calculations to quantify the magnitude of the shift in engineering judgment.

3. **Results and Discussion**:

3.1. Shifting the Cognitive Default: From Satisficing to Broad Consideration

Consistent with Simon's theory of bounded rationality (1957), pre-course data confirmed that novice engineers' default to a "satisficing" strategy, prioritizing a narrow set of familiar criteria. Before the intervention, student focus was dominated by Cost (95%) and Performance (75%), with significantly lower consideration for invisible environmental factors.
Post-intervention, students demonstrated a statistically significant expansion in their evaluative frameworks. The average number of factors considered per student nearly doubled, rising from 5.6 to 10.2 ($p < 0.001$). The effect size was large (Cohen's $d = 1.23$), suggesting that the explicit practice of Multi-Criteria Decision-Making (MCDM) helped students cross a cognitive threshold—moving from simple optimization of a few variables to the management of complex, multidimensional trade-offs.

3.2. Mapping Growth to Sustainability Competencies

The specific factors with the highest growth rates map directly to the development of key sustainability competencies (Wiek et al., 2011), as shown in **Figure 1**:

- <u>Systems-Thinking Competence</u>: The largest increase was observed in Life Cycle Impacts (+68.3%). This suggests that students successfully moved beyond "gate-to-gate" thinking (manufacturing only) to "cradle-to-grave" thinking, a hallmark of systems engineering.
- <u>Anticipatory (Futures) Competence:</u> Significant gains were seen in Toxicity (+63.4%), Persistence (+65.9%), and Bioaccumulation (+75.6%). These metrics require students to anticipate long-term environmental fates rather than immediate process parameters, indicating a shift toward the "Green Chemistry" principle of designing for degradation and safety.

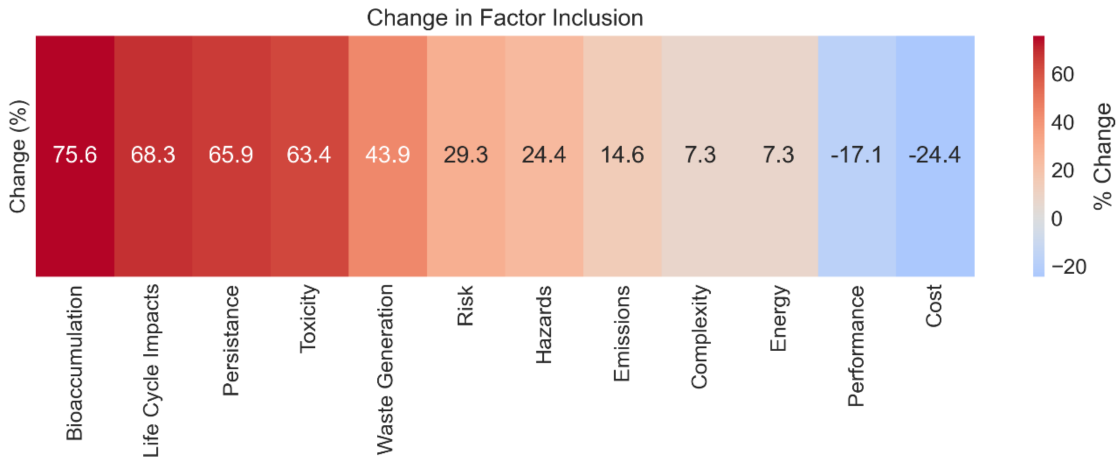

Figure 1. Percent change in students' consideration of various sustainability metrics when making engineering decisions before the Green Engineering course and after. (N=41).

3.3. The "Cost" Anomaly: Bounded Rationality in Action

A notable and perhaps counterintuitive finding was the statistically significant decrease in the consideration of Cost (Figure 1). While the precise reasoning for this shift remains to be confirmed, it may be explained through the lens of bounded rationality (Simon, 1957). As students' limited cognitive load was reallocated toward newly prioritized sustainability metrics (e.g., toxicity, bioaccumulation), they may have 'satisficed' by focusing on the complex new criteria emphasized in the intervention, leading to a relative drop in mentioning the 'obvious' factor of cost. Alternatively, students may have cognitively re-categorized cost from a primary driving variable to a design constraint—a fixed boundary that limits the design space but does not differentiate between the 'best' sustainable alternatives. Further qualitative research is required to determine whether students are truly undervaluing economic viability or are simply prioritizing environmental safety within the specific context of a Green Engineering framework."

Table 1. Percent consideration before, after a Green Engineering course intervention including the statistical significance of the change for each factor. 8 out of the 12 factors showed a significant change before and after the course.

Factor	Before (%)	After (%)	Change (%)	McNemar p	FDR p
Bioaccumulation	4.9	80.5	75.6	<0.0001*	<0.0001*
Life Cycle Impacts	9.8	78.0	68.3	<0.0001*	<0.0001*
Persistance	12.2	78.0	65.9	<0.0001*	<0.0001*
Toxicity	26.8	90.2	63.4	<0.0001*	<0.0001*
Waste Generation	41.5	85.4	43.9	0.0003*	0.0007*
Risk	43.9	73.2	29.3	0.0095*	0.0163*
Hazards	48.8	73.2	24.4	0.0442*	0.0663
Emissions	61.0	75.6	14.6	0.2113	0.2536
Complexity	24.4	31.7	7.3	0.5050	0.5465
Energy	56.1	63.4	7.3	0.5465	0.5465
Performance	56.1	39.0	-17.1	0.0704	0.0939
Cost	85.4	61.0	-24.4	0.0094*	0.0163*

4. Limitations and Future Work

4.1. Distinguishing Vocabulary from Judgment

As a Work-in-Progress, this study relied on a checklist-based survey ("Which factors would you consider?"). A primary limitation is the inability to distinguish between vocabulary acquisition and engineering judgment. It is unclear if students selected "Bioaccumulation" post-course because they genuinely valued it in their decision-making process, or simply because they had recently learned the definition of the term. To claim true competency development, future assessment must move beyond recognition of terms to the application of concepts (Redman et al., 2021).

4.2. Methodological Next Steps: Scenario-Based Assessment

To address this gap, the next phase of this research will implement a Scenario-Based Assessment. Rather than selecting from a list, students will be presented with two competing chemical design pathways, one cheaper/efficient, the other greener/safer, and be asked to: 1) Select a preferred option, 2) Justify their decision in an open-ended format and 3.) Rate their confidence in managing the trade-offs. This approach will allow for the analysis of unprompted consideration, revealing whether students voluntarily deploy sustainability criteria when not explicitly reminded of them by a checklist.

4.3 Study Design and Comparison Groups

Beyond the assessment tool itself, this pilot study lacks a control group, making it difficult to isolate the effects of the MCDM intervention from general student maturation. Future work will employ a quasi-experimental approach by comparing Green Engineering cohorts with students in a senior-level capstone design course (Dringenberg et al., 2018). While capstone students are at a similar developmental stage, they typically receive less formal instruction in structured sustainability metrics, providing a baseline for "standard" engineering judgment. Furthermore, continuing this study across multiple quarters will allow for an increased sample size, providing more robust statistical power to validate the observed shifts in student thinking.

4.4. Durability of Change

Finally, this study captures students' thinking immediately following the intervention. It remains unknown whether this multidimensional reasoning is durable or transferable to other contexts, such as Capstone Design projects (Dringenberg et al., 2018). Future longitudinal data collection is planned to determine if the "scaffolding" provided by MCDM creates lasting mental models that persist after the course ends.

5. Conclusion

This study provides empirical evidence that the "techno-economic" bias prevalent in novice engineering design is not an immutable trait, but a result of bounded rationality that can be expanded through targeted pedagogical interventions. By introducing Multi-Criteria Decision-Making (MCDM) as a formal pedagogical scaffold, this course successfully shifted student cognition from a narrow "satisficing" strategy—dominated by cost and performance—toward the holistic Engineering Judgment required for sustainable practice.

The quantitative results indicate a profound expansion in the students' evaluative frameworks, with a large effect size (Cohen's $d = 1.23$). Specifically, the significant increases in the consideration of Life Cycle Impacts and Bioaccumulation demonstrate that explicit practice with decision matrices helps students internalize the Systems-Thinking and Anticipatory competencies defined by Wiek et al. (2011). Crucially, the simultaneous decrease in Cost dominance suggests that students did not merely "add" concepts to a checklist, but fundamentally restructured their decision-making hierarchy, treating economic factors as constraints rather than sole drivers.For engineering educators, these findings offer a replicable blueprint for meeting the evolving demands of ABET Student Outcome 4.

While the definition of "sustainability" can often feel abstract in the classroom, MCDM provides a concrete mechanism to make invisible ethical and environmental trade-offs visible, calculable, and defensible. Future work will focus on validating these findings through scenario-based assessments to ensure that this broadened awareness translates into durable, applied professional judgment.

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